Columbia River Temperature Assessment
Simulation Methods
EPA Region 10

INTRODUCTION

The objective of the Clean Water Act (as amended by the Water Quality Act of 1987, Public Law 100-4) is to restore and maintain the chemical, physical and biological integrity of the Nation's waters. Each state has developed standards for water quality that are used to judge how well the objectives of the Clear Water Act are being achieved. The water quality standards consist of the designated beneficial uses of the water and the water quality criteria necessary for achieving and maintaining the beneficial uses.

Under Section 303 of the Clean Water Act, the states must identify those waters for which effluent limitations, as required by Section 301, are not sufficient to implement established water quality standards. In accordance with Section 303 of the Clean Water Act, the states of Oregon and Washington have identified portions of the main stem of the Columbia River from the

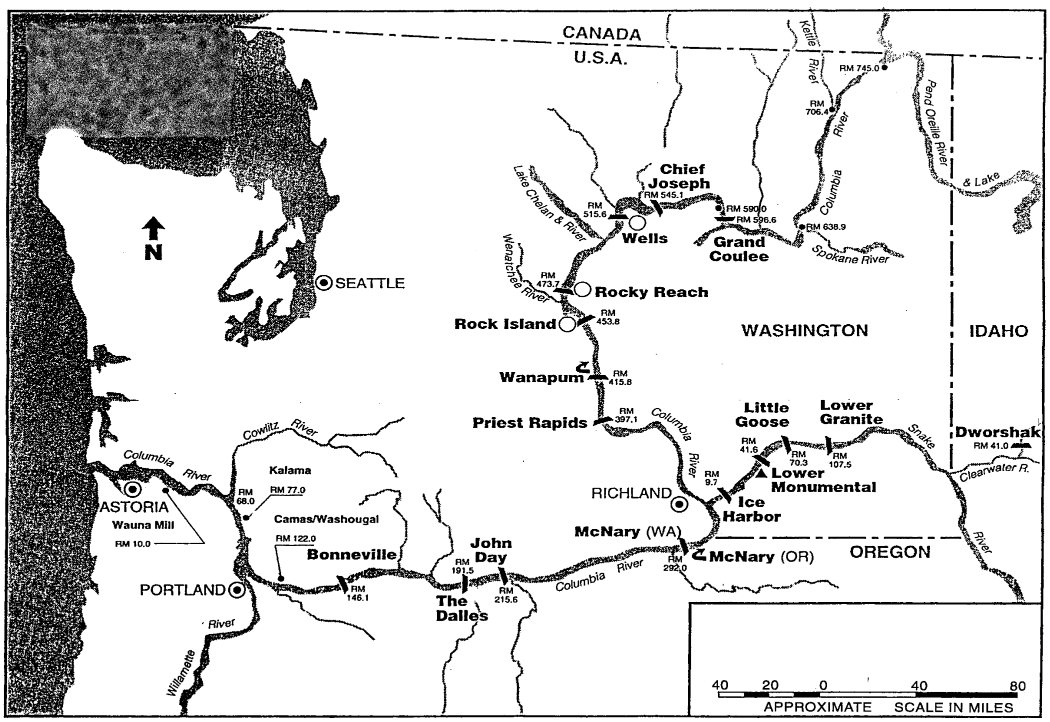

Figure 1. The Columbia and Snake rivers and associated hydroelectric projects in the study area.

International Border (Columbia River Mile 745.0) to the mouth at Astoria, Oregon and the Snake River from Anatone, Washington (Snake River Mile 168.9) to its confluence with the Columbia River (Figure 1) as water quality limited. This designation arises from an analysis of data (Washington DOE, 1998; Oregon DEQ, 1998) showing these waters do not meet water quality standards during all or part of the year. Sources which may contribute to impairment of water quality in these segments of the Columbia and Snake rivers, include:

- Construction of impoundments for hydroelectric facilities and navigational locks which increase the duration of time waters of the Columbia and Snake are exposed to high summer temperatures and which change the thermal response time of the system.

- Hydrologic modifications to the natural river system to generate electricity, provide irrigation water for farmlands and facilitate navigation.

- Modifications of watershed from agricultural and silviculture practices which reduce riparian vegetation, increase sediment loads and change stream or river geometry.

- Operation of pulp and paper manufacturing facilities that results in the discharge of thermal energy and toxic substances, particularly dioxin.

Subsequent to identification of the water-quality limited segments, it is necessary to establish priorities for attaining water quality standards based on the severity of the pollution and the beneficial uses associated with the water body. Water temperature is one of the most frequently occurring constituents on the Oregon and Washington's list of water-quality limited segments on the Columbia and Snake rivers. Those segments of the Columbia and Snake rivers in the study area that are water quality limited for water temperature and for which the listing criteria require a TMDL are given in Table 1.

The first step in establishing priorities for attaining established water quality standards for temperature is to assess the importance of sources that may significantly affect thermal energy budget. Changes in thermal energy budget of the Snake and Columbia rivers relative to the natural, unregulated river system are due primarily to advected thermal energy from point sources, surface water and ground water and to modification of river geometry and hydraulics due to the construction and operation of hydroelectric facilities. The goal of this work is to provide support for the priority-setting phase of theTMDL process by assessing the impacts of the principal sources of thermal energy.

GEOGRAPHY, CLIMATE AND HYDROLOGY OF THE COLUMBIA BASIN

Geography

The Columbia River drains more than 259,000 square miles of southeastern British Columbia in Canada and the Pacific Northwest states of Idaho, Oregon, Washington and Wyoming. The Columbia River rises in the Rocky Mountain Trench and flows more than 400 miles through the rugged, glaciated mountains of southeastern British Columbia before it reaches the U.S.-Canada border near Castlegar, B.C. The Columbia River enters the U.S from the Okanogan Highland Province, a mountainous, area of Precambrian-early Paleozoic marine sediments. The Columbia crosses the western margin of the Columbia Basin, a broad, arid plateau formed by Miocene lava flows of the Columbia Basalt and flows south across the state of Washington. Near Pasco, Washington and the confluence with the Snake River, the Columbia turns west, forming the border between the states of Oregon and Washington and flows more than 300 miles through the Casacade Mountain Range to the Pacific Ocean near Astoria, Oregon.

The headwaters of the Snake River are in Jackson Lake in the Teton Mountains of Wyoming at an elevation of 7000 feet above sea level. It flows west across the Snake Plain, which is also a broad, arid plateau formed by Miocene lava flows of the Columbia Basalt. At the western edge of the State of Idaho it turns north and flows through a deeply incised canyon, emerging near Lewiston, Idaho. At Lewiston, the Snake joins the Clearwater River and flows west through the Palouse Country of eastern Washington, joining the Columbia near Pasco, Washington. In addition to the Clearwater, major tributaries of the Snake in Idaho include the Bruneau, Owyhee, Boise, Payette, Weiser and Salmon rivers.

In addition to the Snake River, the Columbia's largest tributary, other major tributaries include the Kootenai, Clark Fork-Pend Oreille, Spokane, Deschutes and Willamette rivers. The Kootenai lies largely in Canada, but flows through western Montana, northern Idaho and back into Canada before entering the Columbia below Lower Arrow Lake in B.C. The Clark Fork-Pend Oreille has its headwaters on the Continental Divide in Montana, flows through northern Idaho into Pend Oreille Lake and becomes the Pend Oreille River. The Pend Oreille River flows north into Canada before joining with the Columbia River. The Flathead, Blackfoot and Bitteroot rivers are all major tributaries of the Clark Fork. The Spokane River begins in Lake Coeur d'Alene in Idaho and flows west through eastern Washington, entering the Columbia in Lake Franklin D Roosevelt (Lake FDR). Both the Deschutes and Willamette River have their headwaters in Oregon, the Deschutes rising in central Oregon and flowing north across lava flows of the Columbia Basalt, while the Willamette River begins in the Cascade Mountains, flows west to the Willamette Valley, then north to join the Columbia near Portland, Oregon.

Climate

The climate of most of the Columbia River drainage is primarily of continental character, with cold winters and hot, dry summers. Precipitation varies widely depending primarily on topographic influences. The interior Columbia Basin and Snake Plain generally receive less than 15 inches of precipitation annually, while in some of the mountainous regions of Canada the annual precipitation can exceed 100 inches per year.

Air temperature also varies considerably, depending on location. Summertime temperatures in the Columbia Basin and Snake Plain exceed 100º F for extended periods. Temperatures at higher elevations remain cooler. Winters are cold throughout the basin and heavy precipitation falls in the form of snow in the mountain. The snowpack accumulates throughout the winter months as a result of frequent passage of storm systems from the Pacific Ocean. Some of the snowpack is incorporated into the extensive system of glaciers in the basin. However, between the months of March and June, depending on elevation, much of the snowpack begins to melt. The resulting hydrograph is typical of a snowmelt regime.

West of the Cascade Mountains, which includes the lower 150 miles of the Columbia River and all of the Willamette River, the climate has a more maritime character. Winter air temperatures at lower elevations are seldom below freezing and summer air temperatures are seldom above 100º F for long periods. Average annual precipitation west of the Cascades is greater than 40 inches in most areas. Precipitation recorded at coastal stations is typically higher. Below about 5000 feet, most of the precipitation falls as rain with 70 percent or more falling between October and March.

Hydrology

Although the hydrology of the Columbia River system has been modified by the construction of numerous hydroelectric, irrigation, flood control and transportation projects, the hydrograph still has the characteristics of a snowmelt regime. Streamflows are low during the winter, but increase beginning in spring and early summer as the snowpack melts. Melting of the winter snowpack generally takes place in May and June, and streamflows increase until the snowpack can no longer support high flows. Flows then recede gradually during the summer and are derived from reservoir storage and from ground water recession into the fall and winter.

Occasionally, runoff from winter storms augments the base flow and river discharge can increase rapidly. This is particularly true of the Willamette River, which does not depend on the operation of other reservoirs in the Columbia River system. Rather, it is influenced more by precipitation falling as rain and can reach flood stage even with flood control available from reservoirs within the Willamette River system.

Mean annual river discharges for key locations on the main stem Columbia and Snake River and selected tributaries are shown in Table 2.

WATER RESOURCES DEVELOPMENT

The Columbia River and its tributaries have been developed to a high degree. The only segment of the Columbia River above Bonneville Dam which remains unimpounded is the Hanford Reach between Priest Rapids Dam (Columbia River Mile 397.1) and the confluence with the Snake River (Columbia River Mile 324.3). The 11 main stem hydroelectric projects in the U.S. (Table 3), from Grand Coulee Dam to Bonneville Dam, develop approximately 1,240 feet of the 1,290 feet of hydraulic head available in this segment of the Columbia River main stem. Hydroelectric and flow control projects on the main stem of the Columbia River and its tributaries in Canada have resulted in significant control of flow in the Upper Columbia and Kootenai River Basins. The Snake River is also nearly fully developed with a total of 19 dams on the main stem as well as a number of impoundments on its tributaries.

These dams and reservoirs serve many purposes, including irrigation, navigation, flood control, municipal and industrial water supply, recreation and generation of hydroelectric power. There are approximately seven million acres of irrigated farmlands in the Columbia River Basin, including 3.3 million acres in Idaho, 0.4 million acres in Montana, 1.9 million acres in Washington and 1.3 million acres in Oregon (Bonneville Power Administration et al, 1994). The system has the capacity for generating more than 20,000 megawatts of hydroelectric energy and slack-water navigation now extends from the mouth at Astoria, Oregon to Lewiston, Idaho, a distance of more than 460 river miles.

In the U.S., the ownership of the dams in the Columbia River Basin includes federal agencies, private power companies, and public utility districts. The Columbia Treaty between the United States and Canada provides the basis for managing transboundary issues related to the operation of dams and reservoirs on the Columbia River system in Canada.

ROLE OF TEMPERATURE IN WATER QUALITY

For the Columbia and Snake rivers in the State of Washington, the characteristic uses are defined in Chapter 173-201A-030 (2) (b) of the Washington Administrative Code (WAC) as:

(i) Water supply (domestic, industrial, agricultural.
(ii) Stock watering.
(iii) Fish and shellfish:
Salmonid migration, rearing, spawning, and harvesting.
Other fish migration, rearing, spawning, and harvesting.
(iv) Wildlife habitat.
(v) Recreation (primary contact recreation, sport fishing, boating, and aesthetic enjoyment).
(vi) Commerce and navigation.

The characteristic uses for the segments of the Columbia River in Oregon, as defined in the Oregon Administrative Rules (OAR) Chapter 340-041, are similar to those of Washington.

Water quality in the main stem Columbia and Snake rivers is sufficient to protect many of these beneficial uses. An important exception is that of salmonid migration, rearing, spawning, and harvesting. According to the Independent Scientific Group (1996), 200 distinct anadromous stocks returned several million adult salmon and steelhead to the Columbia River prior to development of the basin. Of these stocks, 69 have been identified as extinct and 75 others are at risk of extinction in various parts of the basin. The Independent Scientific Group concluded that the "development of the Columbia River for hydropower, irrigation, navigation and other purposes has led to a reduction in both the quantity and quality of salmon habitat, and most critical, a disruption in the continuum of that habitat."

Water temperature is an important water quality component of habitat for salmon and other cold water organisms in the Columbia and Snake rivers. The criterion for water temperature (Chapter 173-201A WAC and Chapter 340-041OAR) in the main stem Columbia River from the mouth to Priest Rapids Dam (R.M. 397.1) and Snake River from the mouth to its confluence with the Clearwater River (R.M. 139.3) is that temperature shall not exceed 20 ºC due to human activities. For the Columbia River from Priest Rapids Dam (R.M. 397.1) to Grand Coulee Dam (R.M. 596.6), the criterion for water temperature is that the temperature shall not exceed 18 ºC due to human activities.

These criteria were developed specifically to protect cold-water aquatic life, including salmon and steelhead, in the Columbia and Snake rivers. Salmonids evolved to take advantage of the natural cold, freshwater environments of the Pacific Northwest. Temperature directly governs their metabolic rate and directly influences their life history. Natural or anthropogenic fluctuations in water temperature can induce a wide array of behavioral and physiological responses in these fish. These fluctuations may lead to impaired functioning of the individual and decreased viability at the organism, population, and species level. Feeding, growth, resistance to disease, successful reproduction, sufficient activity for competition and predator avoidance, and successful migrations are all necessary for survival.

Temperature preferences for five critical life stages of the salmonids found in the Columbia River system are listed in Table 4. Appendix A contains more detailed information on the preference ranges and effects of temperature on these fish. Additional information can be obtained from two recent EPA-sponsored reports: (1.) A Review and Synthesis of Effects of Alterations to the Water Temperature Regime on Freshwater Life Stages of Salmonids, with Special Reference to Chinook Salmon (1999), by Dale A. McCullough, and (2.) Perspectives on Temperature in the Pacific Northwest's Fresh Waters (1999), by Charles C. Coutant.

IMPACTS OF WATERSHED DEVELOPOMENT ON WATER TEMPERATURE

Once the water-quality limited segments have been identified, Section 303 (d) of the Clean Water Act requires that each State establish a priority ranking determining the severity of the pollution and the uses to be made of the water. One of the first steps in the process is an assessment of the problems associated with a given water quality parameter. The purpose of an assessment is to identify the sources for the water quality parameter of concern.

Water temperature is one of the most frequently occurring parameters on Oregon and Washington's Section 303 (d) lists of impaired waters. The listing of water temperature by Oregon and Washington is based on analysis of data collected by state and federal agencies. These agencies include the Oregon Department of Environmental Quality (DEQ), the Washington

State Department of Ecology (DOE) and the US Army Corps of Engineers (USACE). An analysis of long-term records collected by the USACE as part of the total dissolved gas monitoring study (McKenzie and Laenen, 1998) shows the frequency with which water temperatures have exceeded the water quality criterion at various locations on the Columbia and Snake rivers (Table 5).

Previous studies of the Columbia and Snake rivers (Davidson, 1964; Jaske and Synoground, 1970; Moore, 1969; Independent Scientific Group, 1996) have identified the construction and operation hydroelectric facilities as having a major impact on the thermal regime of the Columbia and Snake rivers. Jaske and Synoground (1970) concluded that the construction of river-run reservoirs on the mainstem of the Columbia River caused no significant changes in the <u>average annual</u> water temperature, but that the operation of Lake Franklin D. Roosevelt (FDR), the reservoir behind Grand Coulee Dam, delayed the time of the peak summer temperature in the Columbia River at Rock Island Dam by about 30 days. Moore (1969) found that both Lake Roosevelt and Brownlee Reservoir on the Snake River caused cooling in the spring and summer and warming in fall and winter. The Independent Scientific Group (1996) concluded that “mainstem reservoirs in the Snake and Columbia rivers have created shallow, slowly-moving reaches of shorelines where solar heating has raised temperature of salmon rearing habitat above tolerable levels” and that changes in the thermal energy budget associated with hydropower system in the Columbia and Snake rivers have resulted in conditions that are suboptimal or clearly detrimental for salmonids,.

Surface and groundwater flows tributary to the Snake and Columbia rivers are also sources of advected thermal energy that have the potential for modifying the thermal energy budget of the main stem. Moore (1969) studied the impact of the Clearwater and Salmon rivers on the main stem Snake and the Kootenai and Pend Oreille rivers on the Columbia during 1967 and 1968. He found that the Clearwater and Salmon rivers cooled the Snake River during some of this period, but at no time did they produce a warming effect. Viewing the Snake as a tributary to the Columbia, Moore (1969) and Jaske and Synoground (1970) concluded that the advected thermal energy from the Snake River increased the temperature of Columbia River during the summer. Moore (1969) estimated that the maximum temperature increase was of the order of 1^{o} C during 1967 and 1968, while Jaske and Synoground (1970) estimated the annual thermal energy contribution of the Snake River to the Columbia River to be on the order of 4,000 megawatts. The Independent Scientific Group (1996) discuss temperature in the tributaries primarily as it relates to habitat in individual tributaries. They conclude that high temperatures in the late summer and fall are detrimental to both juvenile and adult salmon in the mainstem and tributaries, but do not discuss the impact of the tributaries on the thermal energy budget of the main stem.

The only significant permitted point source discharge of thermal energy to the Columbia and Snake rivers in the study area (Figure 1) is the Potlatch Corporation discharge to the Snake River at Snake River Mile 139 near the confluence of the Snake and the Clearwater rivers. The Potlatch facilities discharges approximate 130 megawatts of thermal energy to the Snake River. The Hanford Project discharged as much as 23,000 megawatts of thermal energy and had significant impacts on the temperature of the Columbia River (Jaske and Synoground,1970; Moore 1969; Yearsley, 1969). However, this discharge was discontinued in the 1970’s.

STUDY OBJECTIVES

For the segments of the main stem Columbia and Snake rivers included in the study area (Figure 1), the impacts of watershed development on the thermal energy budget are associated with the operation of dams and reservoirs and advected energy from tributaries, groundwater and point sources. The objective of this study is to determine, for a given sequence of hydrology and meteorological conditions, the relative impacts of the operation of dams and reservoirs on the thermal energy budget of the main stem Columbia and Snake rivers compared to the impact of thermal input from surface and groundwater inflows. The specific objectives are:

- Estimate the magnitude and frequency with which daily-average water temperatures in the Columbia and Snake rivers will exceed the benchmark of 20° C under existing conditions of river management and a representative record of river hydrology and meteorology

- Estimate the magnitude and frequency with which daily-average water temperatures in the Columbia and Snake rivers will exceed the benchmark of 20° C with all dams on the Columbia River below Grand Coulee Dam in place and all dams removed.

- Estimate the magnitude and frequency with which daily-average water temperatures in the Columbia and Snake Rivers will exceed the benchmark of 20° C under existing conditions of river management and with major tributaries and point sources constrained to maintain temperatures less than 16° C.

- Characterize the uncertainty of these estimates for purposes of assessing the risks associated with potential management decisions in the Columbia and Snake rivers.

The benchmark of 20° C was chosen because it is at water temperatures greater than this that adult salmon are at risk. Karr et al (1998), for example, used 20° C as a benchmark, representing it as an upper incipient lethal water temperature for migrating salmon and steelhead. Based on a literature review, Karr et al. (1998) determined that 20° C (68 degrees F) is the point where the zone of lower resistance starts for immigrating adult salmon and steelhead. Results from the Columbia River Thermal Effects study reported by Bonneville Power Administration and others (1994) (Figure 3-4) show that 20° C is the water temperature were the zone of lower resistance starts for immigrating adult salmon and steelhead. At water temperatures higher than 21.1 degrees C (70 degrees F) salmonids are in a lethal range where the time it takes to kill the fish declines rapidly. More detailed information on temperature requirements for several species of salmonids is contained in Appendix A.

A one-dimensional mathematical model of the thermal energy budget that simulates daily-averaged water temperature under conditions of gradually varied flow is used to achieve this objective. Models of this type have been used to assess water temperature in the Columbia River system for a number of important environmental analyses. The Federal Water Pollution Control Administration (Yearsley, 1969) developed and applied a one-dimensional thermal energy budget model to the Columbia River as part of the Columbia River Thermal Effects Study. The Bonneville Power Administration and others (1994) used HEC-5Q, a one-dimensional water quality model, to provide the temperature assessment for the System Operation Review and Normandeau Associates (1999) used a one-dimensional model to assess water quality conditions in the Lower Snake River for the US Army Corps of Engineers.

The use of a one-dimensional model of daily-averaged temperatures is appropriate for answering basic questions regarding the impacts of watershed development on water temperature. Important issues associated with water temperature in the main stem Columbia and Snake Rivers for which this type of model is not appropriate include:

- Instantaneous temperatures: The water quality standards for the Columbia and Snake rivers in both Oregon and Washington are written in terms of instantaneous temperatures. The model used for this analysis does not simulate instantaneous water temperatures. Therefore, the model results cannot be compared directly to the criteria for water temperature established by water quality standards of Oregon and Washington.

- Lateral and vertical variations in water temperature: The thermal energy budget model simulates the daily-averaged, cross-sectional averaged temperature. Important spatial dimensions of the lotic ecosystem (Independent Scientific Group, 1996) are the riverine (longitudinal), riparian (lateral) and hyporheic (vertical habitat below the river channel). Development of the hydropower system has caused significant changes to the thermal regimes in all these dimensions. The one-dimensional thermal energy budget model results can be used only to characterize the water temperatures in the riverine or longitudinal dimension of habitat. The model results correspond approximately to the state variable, “thalweg temperature”, used by the Independent Scientific Group (1996).

- Unsteady flow: The model uses the methods of gradually-varied flow to characterize river hydraulics. The model objectives may not be met under conditions of storm or very rapid snowmelt events.

MATHEMATICAL MODEL DEVELOPMENT

System Boundaries

The boundaries of the Columbia River system for the assessment of water temperature include the Columbia River from the International Boundary (R.M. 745.0) to Bonneville Dam (R.M. 145.5) and the Snake River near Anatone, Washington (R.M. 168.9) to its confluence with the Columbia River near Pasco, Washington. With the exception of Grand Coulee Dam and its impounded waters, Lake FDR, all the hydroelectric projects on these segments of the Columbia and Snake rivers have limited storage capacity and are operated as run-of-the-river reservoirs. Because of its large storage capacity (Table 3), Lake FDR is used for flood control as well as providing water for irrigation and generation of hydroelectric power. Typical reservoir elevations for Lake FDR show a substantial annual variation (Figure 2).

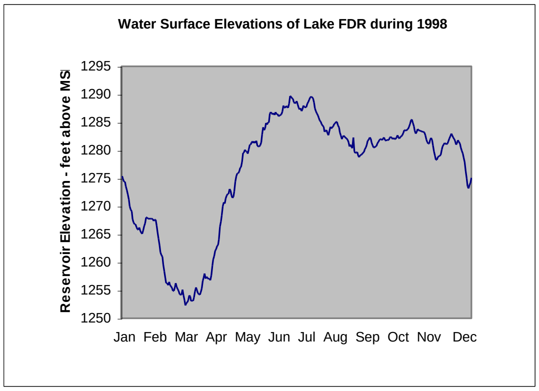

Figure 2. Surface elevations in Lake Franklin D Roosevelt during 1998

Run-of-the-river reservoirs are those for which reservoir elevation is kept more or less constant and water coming in to the reservoir is passed directly through the reservoir. With the exception of Lake FDR, projects on the Columbia and Snake rivers are generally operated as run-of-the river reservoirs. Typical of the operation of run-of-the-river reservoirs are Lower Granite Reservoir and John Day Reservoir, the two largest run-of-the-river reservoirs on the Snake and Columbia rivers. Surface elevations for these two reservoirs during 1998 are shown in Figures 3 and 4, respectively.

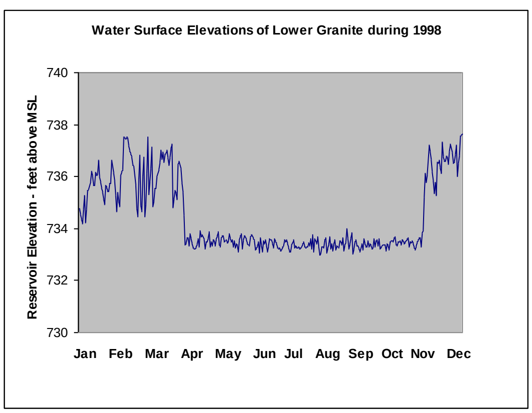

Figure 3. Surface elevations in Lower Granite reservoir during 1998

The differences between the run-of-the-river reservoirs and Lake FDR, with respect to both their modes of operation and storage capacity, give rise to differences in their respective thermal regimes. For the run-of-the-river reservoirs, the spatial variability of temperature within a cross-section perpendicular to the direction of flow is generally less than 1^0 C (McKenzie and Laenen, 1998) except near the forebay of some dams. In Lake FDR, vertical variations in water temperature of up to 5^o C have been observed at various locations along the longitudinal axis of the reservoir. Because of this difference in the thermal regimes, the run-of-the-river projects can be modeled as systems with variability in the longitudinal direction, only. Lake FDR, however, is treated as a system with both vertical and longitudinal spatial variability using the water quality modeling system, CEQUAL-W2 (Cole and Buchak, 1995). The assessment of water temperature in Lake FDR will be described in a later study.

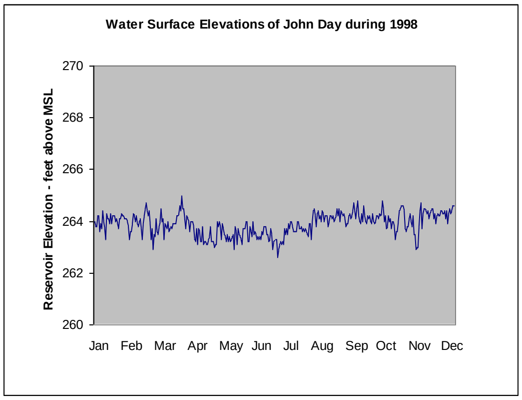

Figure 4. Surface elevations in John Day reservoir during 1998.

This report describes the development and application of a one-dimensional thermal energy model for the run-of-the-river reservoirs. The system boundaries for the model of the run-of-the-river segments are the main stems of the Columbia River from the tailwaters of Grand Coulee Dam (Columbia R.M. 596.6) to Bonneville Dam (Columbia R.M. 145.5) and the Snake River from its confluence with the Grande Ronde River (Snake R.M.168.7) to its confluence with the Columbia River near Pasco, Washington (Snake River Mile 0.0). Advected thermal energy from groundwater, point sources and major tributaries (Table 6) to these segments are treated as inputs to the main stem rivers in this analysis.

Thermal Energy Budget

The thermal energy budget method has proven to be a useful concept for simulating temperatures in aquatic environments. Concern regarding the impact of reservoir operations on water temperature and aquatic ecosystems provided the motivation for early applications of the method (Burt, 1958; Delay and Seaders, 1966; Raphael, 1962; Edinger et al., 1974). Prior to the passage of the Clean Water Act, numerous studies of the thermal discharges by the electric power industry were also performed using the energy budget method (Edinger et al, 1974). Brown (1969, 1970) applied the method to simulating stream temperature increases resulting from the removal of riparian vegetation during logging operations. Recent applications of the energy budget method have focused on water quality planning issues related to reservoir operations (Cole and Buchak, 1995; Normandeau Associates, 1999), watershed management (Bonneville Power Administration and others, 1994, Foreman et al, 1997; Risley, 1997; Rishel et al, 1982; Sinokrot and Stefan, 1993) and fisheries habitat enhancement (Bartholow, 1989; Theurer et al, 1984).

Thermal energy budget models for aquatic ecosystems are developed either in an Eulerian frame of reference, in which the reference system is fixed in space and through which the water flows; or a Lagrangian frame of reference in which the reference system moves with the fluid. The one-dimension thermal energy model for estimating the state variable, water temperature, stated in terms of the Eulerian viewpoint and assuming there is no longitudinal dispersion is:

$$\rho C_p A_x \frac{\partial T}{\partial t} + \rho C_p \frac{\partial (QT)}{\partial x} = w_x H_{net} + S_{adv} + w_T \tag{1}$$

where,

Δ = the density of water, kg/meter^3,

C_p = the specific heat capacity of water, kcal/deg C/kg,

A_x = the cross-sectional area of the river at the distance, x, meter^2,

T = the true water temperature, ^oC,

Q = the river flow rate, meter^3/second,

w_x = the width of the river at the distance, x, meters,

H_{net} = the heat flux at the air-water interface, kcal/meter^2/second,

S_{adv} = the heat advected from tributaries and point sources, kcal/meter/second,

w_T = a random water temperature forcing function, ~N(0, Γ_Q(t))

x = the longitudinal distance along the axis of the river, meters,

t = time, seconds.

In the Lagrangian frame of reference, the systems model for estimating the water temperature, using the energy budget method and assuming no longitudinal dispersion, is given by:

$$\rho C_p A_x \frac{dT}{dt} = w_x H_{net} + S_{adv} + w_T \tag{2}$$

where the symbols are as previously defined.

Equations (1) and (2) are the state-space system equations for water temperature in the Eulerian and Lagrangian frame of references, respectively. Water temperature measurements also provide an estimate of the system state. The observation model for water temperature at the kth time interval is given by (Gelb et al, 1974)

$$Z_k = H_k T_k + v_k \tag{3}$$

where,

Z_k = the measured value of the water temperature, ^oC,

H_k = the measurement matrix,

v_k = the measurement error, ~N(0, Γ_R)

Γ_R = the variance of the measurement error, v_k.

Heat Exchange Across The Air-Water Interface

Heat exchange across the air-water interface is generally the major source of thermal energy for lakes, rivers and reservoirs. As is the case for the applications described above, this study assumes the net exchange of thermal energy, H_{net}, across the air-water interface can be described by:

$$H_{net} = (H_s - H_{rs}) + (H_a - H_{ra}) + H_{evap} + H_{cond} - H_{back} \tag{4}$$

where,

H_{net} = Net heat exchange across the air-water interface, kcal/meter^2/second,

H_s = Shortwave solar radiation, kcal/meter^2/second,

H_{rs} = Reflected shortwave solar radiation, kcal/meter^2/second,

H_a = Longwave atmospheric radiation, kcal/meter^2/second,

H_{ra} = Reflected atmospheric radiation, kcal/meter^2/second,

H_{evap} = Evaporative heat flux, kcal/meter^2/second,

H_{cond} = Conductive heat flux, kcal/meter^2/second,

H_{back} = Blackbody radiation from the water surface, kcal/meter^2/second.

State Estimation Methods

Mathematical models used to simulate water quality in lakes, rivers and reservoirs have traditionally been deterministic models. That is, state estimates from the model are treated as being exactly determined by preceding events in time or adjacent events in space rather than as random variables. It is very seldom the case that the deterministic state estimates from process models can be reconciled precisely with state estimates obtained with standard measurement devices such as thermistors and DO probes. Model developers have attempted to resolve this problem by invoking a process most often described in terms of two steps. The first step is labeled “calibration” and the second step either “verification” or “validation”. In the first, or so-called “calibration” step, the output of the model is compared to a set of observations. If the output of the mathematical model does not agree with the measurements, the parameters of the model are adjusted, or “calibrated”, until there is some form of agreement between simulated and observed results. An important assumption, rarely stated, in the application of this process is that state estimates obtained with measurement devices are without error or uncertainty. While some effort has been made to formalize the “calibration” process (e.g., Thomann, 1982, vandeHeijde,????), there is no consistent approach for determining when the calibration process is complete, nor quantifying the uncertainty of either the parameters or the state estimates. The water quality simulation package, QUAL2E (Brown and Barnwell, 1987), includes algorithms for estimating uncertainty using either Monte Carlo methods or propagation of uncertainty by first-order methods. The first-order methods used in QUAL2E are, in fact, similar to the variance propagation methods derived for the *prediction* mode of nonlinear forms of the Kalman filter, described below. The methods used in QUAL2E do not, however,account for either systems model or measurement model error. Furthermore, estimates of parameter uncertainty must be obtained in an unspecified manner, independently from the application of the simulation package. The software documentation provides a range of uncertainty estimates (Table VI-1, Brown and Barnwell, 1987) obtained from a survey of other studies, but concludes simply that: "The burden of verifying and confirming input variance estimates for a particular application lies with the user." The groundwater programming package, MODFLOWP, (Hill, 1994) provides a formal method for solving the so-called inverse problem of estimating model parameters and their confidence intervals from the data. The parameter estimation algorithms can be applied to a broad class of problems, including surface water analysis. The model is complex and data requirements are substantial. The available literature revealed no applications of this programming package to solving the inverse problem for surface water models.

Many studies do not even attempt to quantify the adequacy of the "calibration" process. For example, the criteria used in the "calibration" process for a mathematical model of temperature and biological productivity in the Lower Snake River (Normandeau Associates, 1999) were that "the output reproduced general patterns and long terms averages of observed data or knowledge". In the second step, "validation" or "verification", output from the "calibrated" model is compared to observations from an independent data set. The degree to which the simulations and observations agree is subjected to some form of hypothesis testing to determine model "validity". While goodness-of-fit criteria have been proposed by some (Bartholow, 1989; vandeHeijde,????), many studies use qualitative statements to support the conclusion that the model has been "validated". The study of the Lower Snake River, referenced above, concludes the verification process by simply stating that "the calibrated model predicts correct seasonal warming, maximum temperatures, and fall cooling."

A joint study of the Columbia River system, the Systems Operation Review (Bonneville Power Administration et al, 1994), relied on a water quality model, HEC5Q of the Columbia River to evaluate complex system operations strategies and provide support for an environmental analysis required by the National Environmental Policy Act (NEPA). While the report of the model studies invokes the terms calibration and verification, no quantitative tests or results are provided. In the case of the water temperature simulations, the report simply states "The model has been shown to adequately represent the thermal responses throughout the river system for summer months ----".

These examples typify the lack of rigor and consistency in the traditional approaches. Oreskes et al (1994) have noted the philosophical problems associated with attempting to verify or validate deterministic earth science models. Matalas and Maddock (1976) observed that

> "Calibration implies that for the parameters of the identified model, one has control over the degree of accuracy in a particular estimation. Verification implies that the identified calibrated model, tested under controlled conditions, mimics the physical system of interest and therefore the identified calibrated verified model is to be accepted.
>
> <u>The words identification, calibration and verification are misleading because of their connotation of greater understanding of and control over the physical processes than actually exists</u> (emphasis added)."

The techniques of state estimation avoid many of the philosophical difficulties associated with traditional modeling approaches by assuming the state estimates are random variables and that there is error associated with both the systems model and the measurement model. The methods of state estimation formulate the problem in terms of a process or systems model (Equation (1) or (2)) and a measurement model (Equation (3)).

The systems model includes both a deterministic and probabilistic component. The deterministic component of the systems model is based on the known laws of physics, chemistry and biology. In this case the systems model is based on scientific and empirical knowledge of the thermal energy budget. The probabilistic component represents the uncertainty in the systems model. Depending on the nature of the problem, the uncertainty can be due to level of spatial or temporal aggregation, model structure; parameter estimation and input variability. The detail with which previous studies have treated systems uncertainty in water quality or quantity studies ranges from the very basic (Moore et al, 1976) to the very complex (Rajaram and Georgakakos, 1987).

The measurement model (Equation (3)) reflects the fact that estimating the state of a system with some form of measuring device cannot be done without some uncertainty. This uncertainty arises from inherent error in the measurement device, sampling error and mapping of point observations to block observations. The matrix, $\mathbf{H_k}$, describes which state variables or combinations of state variables are being sampled at time, k.

The goal of state estimation methods is to combine the estimates from the systems model (Equation (1) or Equation (2)) and the measurement model (Equation (3)), when measurements are available, to obtain an optimal estimate of the system state. As described by Gelb et al (1974) there are three types of state estimation problems based on the time of the estimate compared to that of the last measurement of the system state. When the state estimate precedes the last measurement, it is a *smoothing* problem; when it coincides with the last measurement it is *filtering*; and when it occurs after the last measurement it is *prediction.* The Kalman filter (Gelb et al, 1974; Schweppe, 1973) gives an unbiased, minimum squared error estimate of the system state for the *filtering* and *predictio*n *problems* when all the parameters in Equation (1) or (2) and Equaation (3) are known. For the *filtering* problem, the Kalman filter combines the state estimates from the systems model and the measurement model. The two estimates are combined using a weighting factor determined by the relative uncertainty of the systems model compared to the uncertainty of the observation model. The weighting factor, the Kalman gain matrix, K_k, is derived by constraining the error in the estimate to be unbiased and to have a minimum mean square error.

For linear systems, the complete Kalman filter algorithm is

Systems Model:	$\underline{T}_k = f_{k-1}\,\underline{T}_{k-1} + \underline{w}_{k-1}$	$\underline{w}_k \sim N(\underline{0},\Sigma_Q)$	(5)
Measurement Model:	$\underline{T}_k = H_k\,\underline{T}_k + \underline{v}_{k-1}$	$\underline{V}_k \sim N(\underline{0}, \Sigma_R)$	(6)
System Extrapolation:	$\underline{T}_k(-) = f_{k-1}\,\underline{T}_{k-1}(+)$		(7)
Error Covariance Extrapolation:	$P_k(-) = f_{k-1}\,P_{k-1}(+)f_{k-1} + \Sigma_Q$		(8)
State Estimate Update:	$\underline{T}_k(+) = \underline{T}_k(-) + K_k[\underline{z}_k - H_k\,\underline{T}_k(-)]$		(9)
Error Covariance Update:	$P_k(+) = [I - K_k\,H_k]\,P_k(-)$		(10)
Kalman Gain Matrix:	$K_k = P_k(-)H_k^T[H_k\,P_k(-)H_k^T + \Sigma_R]^{-1}$		(11)
Innovations Sequence:	$\nu_k = z_k - H_kT_k(-)$		(12)

Where (-) denotes values at time, k, prior to filtering, (+) denotes values at time, k, after filtering and f_k is the systems matrix.

The Kalman gain matrix, K_k, is positive definite, so that the updated error covariance (Equation (10)) is always equal to or less than the extrapolated error covariance (Equation (8)).

The filter equations (Equations (5)-(12)) are used for the *prediction* problem as well. However, in the *prediction* problem, the Kalman gain matrix, K_k, is zero because there are no observations available. In this case, only the systems model provides an estimate of the state. However, an additional feature of the Kalman filter is that it provides an estimate of the error covariance (Equation (8)) for both the *filter* and the *prediction* problems.

The innovations sequence (Equation 12) provides a quantitative measure for parameter estimation. The innovations sequence is simply the difference between the system extrapolation (Equation (7)) and the actual measurement, z_k. If one is thinking in terms of the traditional approach to model development, the innovations sequence is superficially similar to comparing the simulated state estimates with the measured state estimates. Formally, it is different in that the system extrapolation is a function of the previous measurements and, in addition, the innovations sequence incorporates aspects of both the systems error and the measurement error. When the filter is optimal, the innovations sequence is unbiased and uncorrelated in time. That is,

$$E\{\nu_k\} = 0$$

and

$$E\{\nu_i \nu_j^T\} = 0, \text{ for } i>j$$

where E is the expectation operator. When the innovations sequence satisfies these criteria it means all the deterministic information has been extracted from the systems model.

When the model parameters are unknown, the innovations sequence can, therefore, be used as way of finding a parameter set which provides optimal estimates. That is, the model parameters can be adjusted until the criteria given above are satisfied.

Although state estimation techniques provide the basis for dealing with issues of model and measurement uncertainty in a more rational and consistent manner than do the traditional deterministic modeling methods, there have been relatively few applications of state estimation techniques in the field of surface water modeling. Lettenmaier (1975), Moore (1973), Moore et al (1976) and Dandy and Moore ((1979) used state estimation methods to evaluate strategies for designing surface water quality monitoring systems. Lettenmaier and Burges (1976) provided a tutorial on state estimation for application to measurement system design, model building, and assessment; and data extension. Koivo and Phillips (1976) used state estimation techniques to show how one could obtain optimal estimates of DO, BOD, and stream parameters for a dynamic water quality model. Beck and Young (1976) studied the use of the Extended Kalman Filter (EKF) for purposes of system identification of DO-BOD model structure. Bowles and Grenney (1978) incorporated sequential EKF's into a surface water quality model to estimate nonpoint source loadings over a 36.4-mile stretch of the Jordan River, Utah.

These examples represent some of the effort made by researchers to apply or to demonstrate how to apply state estimate methods to surface water quality modeling. That these efforts achieved limited success in terms of encouraging wider use of the methods could be due to a number of factors. First of all, the methods appear somewhat complex, even though the most common technique, the Kalman filter, is a close relative of linear regression use the method of least squares. It is also true that the structures of models for many surface water state variables, particularly the biological constituents, cannot always be well-defined. When the model structure is difficult to identify, the use of state estimation techniques may not be entirely satisfactory (Beck and Young, 1976). Solving the inverse problem for surface water quality model problems can also be technically difficult. The inverse problem can also carry data-gathering burdens which are not compatible with the time and capital resources available to natural resource and regulatory agencies. Water temperature, given the state of the art, is one state variable for which the techniques of state estimation are well suited. It is simple and comparatively inexpensive to gather water temperature data. In addition, there is general agreement among researchers regarding the structure of the thermal energy budget model. Algorithms for estimating rates of energy transfer for the various components of the energy budget have also been well developed. Therefore, state estimation methods were developed to make estimates of the system state and its uncertainty for water temperature in the Columbia and Snake river main stems.

To obtain an estimate of the water temperature from the systems model, it is first necessary to decide whether to implement the solution method with a Lagrangian point of view or with an Eulerian point of view. Given the spatial and temporal complexity of the natural environment, most mathematical models using the thermal energy budget method are developed in the Eulerian frame of reference. The Eulerian frame of reference is a more intuitive way of viewing changes in concentrations simply because most measuring devices are fixed at a specific location rather than moving with the water. It is also less difficult to incorporate spatial complexity into the Eulerian framework, and, therefore, easier to add more spatial dimensions as well as more complex spatial processes such as dispersion and turbulent diffusion.

Most systems models using the Eulerian framework solve Equation (1) with either finite difference (Brown and Barnwell, 1987; Cole and Buchak, 1995; Sinokrot and Stefan, 1993; Smith, 1978) or finite element methods (Baca and Arnett, 1976). These models have generally proved valuable for simulating water temperatures in a variety of aquatic environments. However, it is well known that solutions to equations of the type characterized by Equation (1), using finite difference or finite element techniques, are subject to stability and accuracy problems (e.g., O'Neill, 1981). For water quality models, stability problems are generally not as serious as accuracy problems. When a solution becomes unstable, it is usually obvious and can generally be eliminated by reducing the time step. Accuracy problems are more pervasive and often subtle. Of particular concern to developers of finite difference and finite element methods are problems, commonly characterized as numerical dispersion, associated with the propagation of phenomena with short wavelengths. Numerical dispersion is most evident in the propagation of sharp spatial gradients when advection dominates the system. The resulting simulations can have spurious damping of high frequencies or oscillations. They are caused by differences between the rate at which the numerical scheme propagates the solution in space and the rate at which the solution would be propagated in space by the natural system.

Solution techniques based on the Lagrangian point of view (Jobson, 1981) avoid the accuracy problems associated with Eulerian methods but lack the computational convenience of a fixed grid. However, efficient accurate solution methods have been proposed which combine some of the virtues of each point of view (Cheng et al, 1984; Yeh, 1990; Zhang et al, 1993). In these hybrid Eulerian-Lagrangian methods, advective processes are treated with a Lagrangian formulation. Diffusion or dispersion processes, if present, are treated with an Eulerian formulation. With many of the hybrid methods, the need to satisfy the Courant criterion can be relaxed. In addition, the application of state estimation techniques, as discussed below, is greatly simplified. Hybrid methods do not always eliminate numerical dispersion. However, Yeh (1990) found that the use of hybrid methods with single-step reverse particle tracking (SRPT) was definitely superior to the Eulerian method using upwind method. Zhang et al (1993) found that hybrid methods using SRPT introduced some numerical dispersion, but that a modified form of SRPT eliminated the numerical dispersion. Cheng et al (1984) reported that when linear interpolation was used with hybrid solution techniques, numerical dispersion was similar to that of upwind methods. Cheng et al (1984) were able to eliminate numerical dispersion from the hybrid method by using second-order Lagrangian polynomial interpolation.

The mixed Eulerian-Lagrangian method using reverse particle tracking was chosen as the solution technique for simulating water temperature in the Columbia River system for the following reasons:

- It reduces the state-estimation (filtering and prediction) problem to one of a single state variable rather than one requiring a state variable for each finite difference or finite element grid point.

- It is relatively easy to avoid instabilities in the solution when the Courant stability criterion is exceeded.

- It provides the flexibility to expand the scope of model to include diffusion-like processes and/or more spatial dimensions.

- Although the method does not completely eliminate numerical dispersion, the results of studies described previously show that the method's ability to propagate high frequencies is generally superior to Eulerian methods. Tests of reverse particle tracking and the numerical method used by WQRRS, a water quality model commonly used by the US Army Corps of Engineers (Smith, 1978; Normandeau Associates, 1999), showed that reverse particle tracking propagated high frequencies more accurately than WQRRS (Appendix B).

The mixed Eulerian-Lagrangian method uses the concept of reverse particle tracking to implement the Lagrangian step. The river system is divided into N segments, not necessarily of the same spatial dimensions. Within each segment, however, the geometric properties of the river system are assumed to be constant during a given time step. Water temperature values are recorded only on the boundaries between segments. As an example of the method, consider the Segment J. (Figure 5). At the end of a computational time step, $t = t_{k+1}$ a particle at the downstream end of the Segment J, is flagged. The flagged particle is tracked backward in time upstream until its position at the beginning of the time step, $t = t_k$, is located. The location of a particle tracked in this manner will, in general, not be precisely on a segment boundary, where water temperatures are stored by the computational scheme. Therefore, it is necessary to determine the water temperature of the particle at the beginning of the time by interpolating between the points where water temperatures are recorded. In the solution technique used in this study, this is accomplished with a second-order polynomial using Lagrangian interpolation (Press et al, 1986). Once the location of the particle and its initial water temperature are determined for the beginning of the time step, the particle is followed back downstream to its location at the end of the time step (the downstream end of Segment J). The change in water temperature for the particle during this time step is estimated using Equation 2

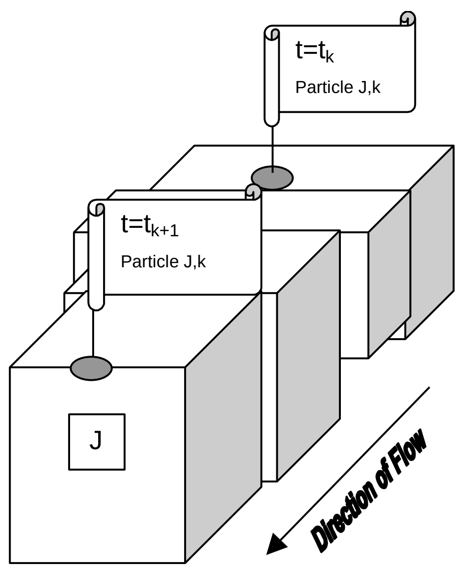

Figure 5. Schematic for reverse particle tracking method

The information required for obtaining a solution to Equation 2 using reverse particle tracking includes

- River width as a function longitudinal distance during the time step

- Cross-sectional area as a function of longitudinal distance during the time step

- River velocity as a function of longitudinal distance during a time step

- Net heat exchange as a function of longitudinal distance during a time step.

The hydraulic characteristics of the unimpounded reaches of the river system are estimated from power equations relating mean velocity, area and width (Leopold and Maddock, 1953). That is,

$$U = A_u\, Q^{B_u} \tag{13}$$

$$A_x = A_a\, Q^{Ba} \tag{14}$$

$$W_x = A_w\, Q^{Bw} \tag{15}$$

where,

U = the river velocity, feet/second,

A_x = the cross-sectional area, feet^2,

Q = the river flow, cfs,

W_x = the river width, feet,

The coefficients, A_u, B_u, A_a, B_a, B_u, A_w, and B_w, are estimated by simulating river hydraulics conditions under various flow conditions using the methods of steady gradually varied flow (USACE-HEC, 1995). The gradually varied flow method gives estimates of the average longitudinal velocity, U, the average water depth, D, and and the river width, W_x as a function of river flow. The coefficients are determined by fitting Equations (13)-(15) to the resulting estimates using the method of least squares.

For the impounded reaches, the water surface elevation is assumed to remain constant, such that the depth and width remain constant at any cross-section and the velocity, U, is simply

$$U = Q/(W_x{*}D) \tag{16}$$

Exchange of thermal energy across the air-water interface is estimated from Equation (3) using formulations for components of the heat budget as described by Water Resources Engineers (1968).

Time and Length Scales

To accomplish the management objectives of the analysis it is necessary to simulate daily-averaged water temperatures as a function of longitudinal distance in the Columbia and Snake rivers. This establishes an approximate lower limit on system time scales and on data requirements. Stability and accuracy issues associated with solutions to Equation (3) can impose a requirement of even smaller time increments to obtain reliable solutions. However, the simulated results for time scales less than a day are valuable only in terms of their contribution to the solution accuracy. Since the time scale of the input data is equal to or greater than one day, there is no physical significance to higher frequency output associated with the need to obtain a stable solution.

In an effort to include the environmental variability due to hydrology and meteorology, the largest time scales are of the order of two decades. This time scale is constrained by the hydrologic data available for the Columbia River system under existing management. Existing management in this case means operation of the system subsequent to the construction of the last hydroelectric project. The last hydroelectric project was Lower Granite Dam and Reservoir, completed in 1975. The simulation time scale, therefore, was chosen to be the period from 1975 to 1995.

The length scales for the analysis are determined by a number of factors. These include the availability of geometric data, spatial variability in the river geometry and computational stability and accuracy. It is often the case that data availability provides the most severe constraint. However, in the case of the Columbia and Snake rivers, within the boundaries of this analysis, there are ample data for describing river geometry in both rivers. The primary factor determining the length scale of this analysis is the need to achieve stable, accurate solutions. Length scales are such that the time it takes a parcel of water to traverse a given computational segment is always equal to or less than one day. For the Columbia and Snake rivers, this results in length scales of the order of 1 to 10 miles.

Rationale for Approach

Idealizing the largest part of the Snake and Columbia River system in terms of a one-dimensional model is based on the assumption that the primary processes affecting the thermal energy budget are advection and the transfer of thermal energy across the air-water interface. This is in keeping with the management objective of providing a primary temperature assessment for developing a TMDL. Based on previous work in the Columbia and Snake rivers (Raphael, 1962; Yearsley, 1969; Jaske and Synoground, 1970), a model of this type should capture the major features of water temperature impacts in this system. As described above, a number of other temperature assessments of the Columbia and Snake rivers (Bonneville Power Administration and others, 1994; Normandeau Associates, 1999) are based on one-dimensional models of the thermal energy budget. The mixed Lagrangian-Eulerian scheme for handling advection was chosen based on studies such as those done by Yeh (1990) and Zhang et al (1993)

DATA SOURCES

Water Temperature

The extensive water temperature data records for the Columbia and Snake River have been assembled and reviewed for quality by McKenzie and Laenen (1998). In addition, McKenzie and Laenen (1998) organized the data in electronic formats for rapid analysis. The results of their work provide a water temperature data set for the Columbia and Snake rivers, which can be used to describe uncertainty in the temperature model. The data quality analysis performed by McKenzie and Laenen (1998) provides a basis for characterizing the uncertainty associated with the measurements.

McKenzie and Laenen (1998) compiled data for the main stem Columbia and Snake rivers. Temperature data for the tributaries included in the analysis were obtained from observations made by the Idaho Power Company, Washington State Department of Ecology (DOE) and the U.S. Geological Survey (USGS). The location of monitoring locations, period of record and frequency of analysis are shown in Table 7.

River Geometry

River geometry is needed to characterize the hydraulic properties of the river as a function of flow and time. The basic data required is elevation of the river channel above mean sea level at a sufficient number of cross-sections so as to adequately describe water depth, water width and velocity as a function of river flow. A number of sources were used to accomplish this. These sources are described in Table 8.

Hydrology

River hydrology data for the main stem Columbia and Snake rivers, as well as the major tributaries were obtained from the records maintained by the U.S. Geological Survey. Gaging stations used in the study are shown in Table 9. Estimates of groundwater return flow were obtained from Hansen et al (1994).

Meteorology

Meteorological data, including barometric pressure, cloud cover, wind speed, air temperature and relative humidity, are required for the thermal energy budget calculations. First order weather stations in the Columbia Basin maintained by the Weather Service and for which data are archived in the National Climatological Data Center (NCDC) include Lewiston, Idaho; Spokane, Washington and Yakima, Washington. Data are available for these locations at three-hour intervals from the NCDC SAMSON data sets. The period of record for each of these stations is shown in Table 10.

Stations with maximum and minimum daily air temperatures are more numerous and are included in the NCDC Local Climatological Data Sets. Air temperature data from selected stations in the Columbia Basin are shown in Table 11.

The US Bureau of Reclamation maintains a network of agricultural weather stations called the AgriMet stations. These stations report daily averages for all of the necessary meteorological data with the exception of cloud cover. They also report daily-averaged solar radiation. Selected stations from the AgriMet network are shown in Table 12.

An analysis of a 24-year record (1/1/72 to 12/31/95) for the four NCDC SAMSON weather stations showed a high degree of correlation between stations for dry bulb and dew point temperature (Table 13). Average annual air temperatures showed more variability among the stations than did dew point. Cloud cover was correlated, though not to the same degree as dry bulb and dew point temperature. Mean annual cloud cover in Yakima differed substantially from that of the other three SAMSON stations in the Columbia Basin. As expected, wind speed showed a much lower correlation among stations as well as more variability in the mean annual value.

PARAMETER ESTIMATION

The parameter estimation process addresses both the deterministic and probabilistic parameters in the model. The deterministic elements include the source term, f_k, and, implicitly, the travel times of parcels in the Lagrangian reference system. The components of the heat budget (Equation 4) and the advected thermal inputs from tributaries and groundwater comprise the source terms. The parameters required to determine the travel times are derived from an analysis of the system hydraulics. It should be noted these parameters are, in fact, not really deterministic. They are, in fact, random variables. However, for the purposes of this analysis the composite error resulting from variability in the so-called deterministic parameters is included in the error term, $\underline{w}_{k-1}$, in Equation (5). Given this assumption, the probabilistic parameters are the means and variances of the error terms for the measurement model and the systems model.

In this study, the parameter estimation process is implemented in three steps. In the first step, the deterministic parameters are estimated, ideally, from first principles or, as is more often the case, from available research. Next, the deterministic parameters estimated in this way are adjusted until the simulated results from the systems model are approximately unbiased. The systems model is unbiased if the mean of the innovation vector is small, where the innovation vector is the difference between time-updated simulations from the systems model and the actual measurements (Van Geer et al, 1991). Assuming the actual measurement bias and their variances are known, the final step in the parameter estimation process is to estimate the variance, Γ_Q, of the systems model.

Hydraulic Coefficients

As described previously, the hydraulic properties of each unimpounded river segment are estimated from relationships of the type given in Equations (13)-(15). One of the primary objectives of the study is to assess the impact of impoundments. It was, therefore, necessary to make estimates of these coefficients for two states of the system; one with dams in place and for one with all the dams removed. For the case in which the dams were in place, the results from the USACE HEC-5Q model of the Columbia and Snake rivers were provided by Nancy Yun of the USACE North Pacific Division Office and are given in Tables C-1 and C-2, Appendix C. The only impounded reach under the present configuration of impoundents is the Hanford Reach. The coefficients in Equations (13)-(15) for the Hanford Reach are given in Table C-3, Appendix C.

For the scenario with dams removed, geometric properties of the Columbia and Snake rivers, obtained from the sources given in Table 8, were used as input data to HEC-RAS (USACE-HEC, 1995), the steady gradually varied flow model developed by the US Army Corps of Engineers Hydrologic Engineering Center. Surface elevations of the Columbia and Snake rivers were estimated for flows of 150,000, 250,000 and 500,000 cfs in the Columbia River and 60,000, 120,000 and 240,000 cfs in the Snake River. For each of these flows, the average water depth, surface width and velocity at selected locations was used to estimate the coefficients in Equations (13)–(15) using the methods of least squares. The coefficients obtained in this manner are given in Table C-4 and C-5, Appendix C.

Water Balance

The daily flow at any location in either river was determined from the sum of estimated groundwater return flow (Hansen et al, 1994) and the daily gaged flow of the main stem headwaters and the tributaries upstream from the location. This assumes that

- information regarding flow changes is transmitted instantaneously to locations downstream.
- Tributary sources other than those shown in Table 6 are negligible.

Heat Budget

The specific form for each of the terms in the heat budget formulation (Equation 4), as used in this and most other studies involving the energy budget method, is based on a compilation of heat budget studies by Wunderlich and Gras (1967). Chapra (1997) and Bowie et al (1985) also have comprehensive discussions of each of the terms in Equation (4) adapted from Wunderlich and Gras (1967). From the work of Wunderlich and Gras (1967), the individual elements of the heat budget are given by

<u>Shortwave (Solar) Radiation</u>

$$(H_s - H_{rs}) = F(M, \ast, D_y) \tag{17}$$

where,

M = the latitude of the site,

$\ast$ = the declination of the sun at the site,

Dy = the day of the year.

<u>Longwave (Atmospheric) Radiation</u>

$$(H_a - H_{ra}) = (1-\forall_{ar})\ 1.23 \times 10^{-16} (1.0 + 0.17\ C^2)(T_{DB} + 273.)^6 \tag{18}$$

<u>Evaporative Heat Flux</u>

$$H_{evap} = \Delta * 8 * E_v * W * (e_o - e_a) \tag{19}$$

<u>Conduction Heat Flux</u>

$$H_{cond} = R_B \left[\frac{T_s - T_a}{e_s - e_a} \right] \frac{p_a}{1013.3} \tag{20}$$

<u>Black Body (Water Surface) Radiation</u>

$$H_{back} = 0.97\ \Phi\ (T_s + 273.)^4 \tag{21}$$

Initial Water Temperatures

Daily water temperatures are not always available for the locations used as initial conditions on the tributaries (Table 6) of the Columbia and Snake. For most stations long-term sampling with a period of two to four weeks provides sufficient data to synthesize stream temperatures using air temperature. In their study of 584 USGS stream gaging stations within the contiguous United States, Mohseni et al (1998) used a nonlinear model of the following type to synthesize water temperatures

$$T_s \quad = \quad \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}} \qquad (22)$$

where,

T_s = the weekly stream temperature,
T_a = the weekly air temperature from a nearby weather station and

∀, ∃, (and µ are determined by regressing the observed water temperature data on the air temperature data by minimizing the squared error with the downhill simplex method (Nelder and Mead, 1965).

Separate functions of the type defined in Equation (22) are used to describe the rising limb and the falling limb.

Mohseni et al (1998) concluded that the method was accurate and reliable at 89% of the streams. Mohseni et al (1998) also found that the method gives good results even when the air temperature measurements were not in proximity to the stream gaging locations.

The parameters obtained for the tributaries following the method of Mohseni et al (1998), for both rising and falling limbs, at each of the input locations, are given in Table 14

For the initial water temperatures on the main stem Columbia River, scroll case and total dissolved gas data from Chief Joseph Dam were combined to provide a long term record. On the Snake River, the USGS data from the monitoring site at Anatone, Washington was combined with data collected by Idaho Power Company and the Columbia River Intertribal Fish Commisson to form a long term record.

Measurement Bias and Error

The analysis of water temperature in the Columbia and Snake rivers by McKenzie and Laenen (1998) provides the basis for an initial estimate of the probabilistic parameters of the measurement model (Equation 3). The data reviewed by McKenzie and Laenen (1998) were obtained from scroll case measurements and measurements made in conjunction with total dissolved gas monitoring. The scroll case measurement reflects the temperature of the water as it enters the generating turbine and is measured by reading the level of a mercury thermometer. The total dissolved gas monitoring program uses a temperature probe located in the forebay of each of the dams and at a depth generally equal to or greater than 15 feet.

The quality, bias, and variability of these data vary considerably from site to site. For the scroll case data, McKenzie and Laenen (1998) report frequent “stepping" of the data. Stepping is characterized by periods of several days when the reported temperature is constant. Scroll case temperatures are measured by visual observations from mercury thermometers and recorded manually, generally on a daily basis. McKenzie and Laenen (1998) suggest that the measurement method may have contributed to "stepping" and may have been due to the frequency with which scroll case temperatures were made and reported in the past.

The variation in data quality makes the task of quantifying measurement bias and error a difficult one. McKenzie and Laenen (1998) report bias in the measurements as high as 2.0 ^oC and variability as high as 2.0 ^oC at certain sites and during certain periods of the year. However, at most sites and for recent data (post–1990), bias is in the range 0.0-1.5 ^oC and variability is generally less than 1.0 ^oC.

Systems Model Bias and Error

The approach to estimating the probabilistic parameters for the systems model (Equation (5)) follows that of Van Geer et al (1991). Initial estimates of deterministic parameters are obtained from some combination of first principles and existing research. This includes the heat transfer across the air-water interface, advected thermal energy from tributaries and point sources and hydraulic properties of the river system. Adjustments are made to certain parameters until the mean of the innovations vector (Equation (12)) is small.

The parameters selected for adjustment are constrained by assuming that any error in the basic heat transfer components (Equations (17)-(21)), the advected energy from tributaries and the hydraulic computations can be aggregated into the systems model error, $\Gamma_Q(t)$. Given these constraints, what remains to be adjusted is the choice of meteorological stations used to estimate the basic heat transfer components.

The choice of appropriate meteorological stations for estimating the heat budget at the spatial scale of this analysis must take into account regional variations in weather under the constraint of a limited number of stations with complete data. The problem is not unique to this study. The analysis of systems operations in the Columbia Basin (Bonneville Power Administration and others, 1994) used the data from three weather stations (Boise, Idaho; Lewiston, Idaho and Spokane, Washington) to develop the heat budget for the Columbia, Snake and Clearwater rivers. These data were used to describe surface heat exchange from and including Brownlee Reservoir on the Snake to the confluence with the Columbia; the Clearwater River from and including Dworshak Reservoir and the Columbia River from the International Border to Bonneville Dam. A study of thermal energy in the Hells Canyon complex by Idaho Power Company (Harrison et al, 1999) used the combined meteorological data from Parma, Idaho and Prairie City, Oregon to predict water temperatures in Brownlee Reservoir from approximately Snake River Mile 335 to Snake River mile 285. Parma, Idaho is approximately 50 miles from Brownlee Reservoir, while Prairie City, Oregon is approximately 100 miles away.

As shown in Table 13, there are strong regional correlations among certain meteorological variables in the Columbia Basin, particularly air temperature, dew point and cloud cover. Regional correlations for wind speed are not as strong due to the strong influence of topography. Furthermore, there is some regional variation in the climate as reflected in the annual average values (Table 13) . Data from two classes of meteorological stations are available to estimate these components as described previously. There are a limited number of Surface Airways (SAMSON) stations reporting the complete suite of meteorological variables. There is extensive coverage of daily maximum and minimum air temperatures from the Local Climatological Data (LCD) . Data from the SAMSON stations were used to expand the spatial coverage for heat budget analysis. This was accomplished by assuming that wind speed, cloud cover, relative humidity and barometric pressure are large-scale phenomena and that air temperature is more of a local phenomenon. Several LCD stations were augmented with SAMSON data in this way to provide more spatial coverage of the surface heat transfer. Meteorological data were assigned to river segments based on a qualitative assessment of local meteorology. A number of combinations of stations were evaluated in an effort to achieve unbiased simulations. The final configuration of stations is given in Table 14.

Using parameters estimated above, estimates of the system model error variance, $\Gamma_Q(t)$, are obtained by adjusting the estimated variance until the theoretical variance for the innovation vector is approximately equal to the sample variance (Mehra, 1972). The theoretical variance is given by (Kailath, 1968):

$$E\{\nu_k \nu_k^T\} = H\, P_k(-)\, H^T + \Sigma_R \tag{23}$$

and the sample variance, S, by

$$S = \frac{1}{m}\sum_{k=1}^{m} \nu_k \nu_k^T \tag{24}$$

This is an iterative process since the innovations vector is a function of the deterministic parameters and the probabilistic parameters. In addition, there is bias and error in the observations (McKenzie and Laenen, 1998) as described previously . The systems model error estimate was obtained by first finding a set of meteorological stations which provided good (in a qualitative sense) agreement. This was followed by an adjustment of measurement bias and error for the total dissolved gas temperature data, within the range estimated by McKenzie and Laenen (1998). The results of this process for the mean of the innovations sequence described more fully in Appendix D. The final values for systems model variance, Σ_Q, and measurement error and bias are given in Table 16.

After completing the parameter estimation process for both the deterministic and probabilistic parameters, the systems model was run in the predictive mode. That is, the measurements were not used to update the state estimate. Running the model in the *predictive* mode provides a way of comparing state estimates from the systems model with the state estimates from the measurement model in a manner similar to the traditional approaches using the “calibration” and “verification” paradigm. The output from these simulations are shown in Figures 6-14. A more extensive discussion of model results when using the model in the *filter* model is given in Appendix D.

MODEL APPLICATION

Scenarios

The goals of this study are to assess the relative contribution of impoundments and tributary inputs to changes in the thermal regime of the Columbia and Snake rivers. To capture the environmental variability in hydrology and meteorology, the 21-year record of stream flows and weather data from 1975 to 1995 is used to characterize river hydraulics and surface heat transfer rates. Tributary temperatures are developed from local air temperatures using the relationship given by Equation (22) and air temperature data for the same 21-year period. The assessment of impacts to the thermal regime of the Columbia and Snake River is based on the following three scenarios

- Scenario 1 This scenario includes the existing configuration of dams, hydrology and meteorology for the period 1975 to 1995 and tributary temperatures estimated from the 21-year meteorologic record using Equation (22)

- Scenario 2 This scenario assumes all the dams on the Columbia River downstream from Grand Coulee have been removed and the four lower dams on the Snake Have been removed. Hydrology, meteorology and tributary temperatures are the same as Scenario 1.

- Scenario 3 This scenario assumes existing configuration of dams, with hydrology and meteorology for the period 1975 to 1995. Tributary input temperatures are estimated from the 21-year meteorologic record using Equation (22), but are not allowed to exceed 16 °C.

For each of these scenarios, daily-averaged water temperatures are simulated and the mean, mean plus one standard deviation, and the mean minus one standard deviation of the simulated water temperatures are compared to the benchmark, 20 °C. The average annual duration with which the simulated temperature exceeds the benchmark, estimated as the number of days in excess of the benchmark compared to the total number of days in the simulation, is used as one measure for assessing temperature impacts. Another measure is the average value of the difference between the benchmark and the values which exceed the benchmark for each of the three simulation types. The standard deviation for these simulation is computed with the Kalman filter (Equations (5)-(11)) in the prediction mode. In the prediction mode, the measurement matrix, H, is set to zero. This means the Kalman gain, K, is always zero and the variance propagation is a result of updating by the systems model only:

$$\Sigma_k = f_{k-1} P_{k-1} f_{k-1}^T + \Sigma_Q \qquad (25)$$

where the (+) and (-) convention has been dropped since there is no updating based on the observations.

The frequency with which the simulated daily-averaged temperatures exceed the benchmark are plotted for each scenario as a function of Columbia and Snake River Mile in Figures 15-20. The error bars in each of the plots represent the frequencies estimated with the simulated means plus one standard deviation and the simulated means minus one standard deviation. The corresponding results for the average magnitude of excursions above the benchmark are shown in Figures 21-26.

Uncertainty and Variability

The objective of this study was to develop a model of water temperature in the main stem Columbia and Snake rivers for the purpose of identifying critical issues for additional study. The scale of important system dynamics is complex in both time and space and the focus in this study was on the space-time complexity rather than on model complexity. The nature of the objectives and the limitations associated with the observations and knowledge of systems dynamics may introduce additional uncertainty and variability into the final results. The analysis method was developed to characterize some of that uncertainty and variability. However, there are a number of issues, which deserve attention in subsequent analyses of water temperature in the Columbia and Snake rivers. These issues include:

- Heat budget - The choice of meteorologic stations to characterize the energy budget was done subjectively, to achieve good (in a qualitative sense) agreement between simulated values and observations. The analysis would benefit from additional studies of the effect of local climatology, particularly wind speed.

- River hydraulics - Particle displacement speeds and system geometry were based on the assumption that gradually varied, steady-state flow methods were appropriate. This assumption is probably reasonable for the scenarios for which the dams are in place and less so for the river without dams. The uncertainties associated with rapidly changing flows are likely to be greatest during the spring and early summer snowmelt periods. It is less likely they will be important during the critical late summer and early fall periods when flows are low and reasonably steady.

- Initial water temperatures - Initial conditions for water temperature of both main stem and tributatries were estimated by synthesizing a record with data from various sources The error introduced as a result is greatest for the main stem temperatures, since the results of the analysis show that the tributaries have little impact on the average temperatures of the Columbia and Snake rivers. The error introduced in the main stream estimates will decrease in the downstream direction.

- Water Balance – The system water balance was derived from flows measured at gaging stations on the main stem Columbia and Snake rivers and their major tributaries in the study area. Withdrawals for irrigation and miscellaneous tributary flow were not included in the water balance. These sources comprise an estimated 5-7% of the flow increment to the Columbia River.

- Filter - The estimation of the systems model error is based on the assumption the filter is optimal. The filter is optimal if the innovations sequence is a zero mean, Gaussian white noise process. Tests for optimality of the filter have been described by Mehra (1970). These tests were not performed on the water temperature innovations sequence, but a visual inspection of the 30-day averages of the innovations sequence (Figures 14-21) suggest the results are autocorrelated. This could be a result of structural errors in the model, as described above, or could be related to observation bias and error reported by McKenzie and Laenen (1998).

Results

For the Columbia River in Scenario 1, the existing conditions, the average annual frequency with which the simulated daily cross-sectional averaged temperature exceeds the benchmark increases from near zero at Wells Dam to somewhat greater than 0.03 at Priest Rapids. The influence of the Snake River leads to an increase of the frequency between Priest Rapids and McNary Dam from 0.03 to 0.13. From McNary Dam to Bonneville the frequency increases more gradually. The range of results for the simulated average plus one standard deviation and the simulated average minus one standard deviation, is of the order of ± 0.03. The average magnitude with which predicted water temperatures exceed the benchmark increases from 0.0 ºC at Grand Coulee Dam to 1.5 ºC at Bonneville Dam.

With all dams removed (Scenario2), the average annual frequency with which the predicted water temperatures exceed the benchmark decreases to approximately 0.03 at Bonneville Dam. The average magnitude decreases to 0.3 ºC. The range of the duration increases slightly compared to the results of Scenario 1 such that the durations associated with the average simulation plus one standard deviation are approximately 0.04 greater than that of the average simulation. The increase in the range of the estimate for the river without dams is due to the increased response time associated with shallower depths and higher velocities. The duration of exceedance and exceedance magnitude properties for Scenario 3, for which tributary temperatures are constrained to be always less than 16 ºC is similar to Scenario 1 on the Columbia River upstream of its confluence with the Snake. Downstream from the confluence with Snake, the , existing conditions.

In the Snake River, with dams in place (Figure 21), the average annual duration of exceedance is relatively high (0.15)at the starting point (Snake R.M. 139.0), drops slightly due to the influence of the Clearwater River, then increases to 0.21 between there and Ice Harbor Dam (Snake R.M. 9.0). Because the Snake is a smaller river, the range of the estimates is also greater than in the Columbia River. When the dams are removed (Figure 23), the analysis predicts that the mean duration of exceedance at Ice Harbor is approximately as the initial point near Anatone, Washington. The magnitude of exceedances in the Snake River for Scenario 1 increase from 1.5 ºC at Anatone to 2.4 ºC at Ice Harbor. When dams are removed (Scenario 2), the average magnitude of exceedance remains the same at Anatone, and increases slightly to 1.6 ºC at Ice Harbor. The Clearwater River has a noticeable impact on water temperatures of the Snake River as shown by the reduction in the frequency for Scenarios 2 and 3 (Figures 24 and 26) with which predicted water temperatures exceed the benchmark at Lower Granite Dam compared to the initial conditions at Anatone.

Conclusions

The results of the analysis lead to the following conclusions:

- The likelihood that both duration and magnitude with which water temperatures exceed the benchmark daily-average water temperature (20 ºC) in the Columbia and Snake River main stems is greater with dams in place than with dams removed. The likelihood of these events remains essentially unchanged when existing conditions are modified such that tributary temperature are constrained to be equal to or less than 16 ºC. That is, the model simulations predict that the impact of hydroelectric projects on water temperature in the main stem Columbia and Snake rivers is greater than that of the major tributaries.

- The initial conditions for the Snake River near Anatone, Washington are such that the average annual duration with which water temperatures exceed the benchmark is approximately 0.15 and the average magnitude with which predicted water temperatures exceed the benchmark is approximately 1.5 ºC.

- The Snake River has a significant impact on the frequency with which predicted water temperatures exceed the benchmark in the Columbia River below the confluence of the Snake and the Columbia.

References

Baca, R.G. and R.C. Arnett. 1976. A finite element water quality model for eutrophic lakes. *BN-SA-540*, 27 pp., Battelle Pacific Northwest Lab., Richland, Wash.

Bartholow, J.M. 1989. Stream temperature investigations-Field and analytic methods. *Instream Flow and Info. Paper No.13,* U.S. Fish and Wildlife Serv. 139 pp.

Beck, B. and P. Young. 1976. Systematic identification of DO-BOD model structure. Journal of Environmental Engineering, ASCE, 102 (EE5): 909-927.

Bowles, D.S. and W.J. Grenney. 1978 Steady-state river quality modeling by sequential Extended Kalman Filter. *Water Resour. Res*, 14: 84-96.

Bowie, G.L., W.B. Mills, D.B. Porcella, C.L. Campbell, J.R. Pagenkopf, G.L. Rupp, K.M. Johnson, P.W.H. Chan and S.A. Gherini. 1985. Rates, constants, and kinetics formulations in surface water quality modeling (second edition). *EPA/600/3-85-040*. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Georgia.

Bonneville Power Administration and others. 1994. Columbia River system operation review, Appendix M, water quality. *DOE/EIS-0170*, Bonneville Power Administration, US Army Corps of Engineers, and US Bureau of Reclamation, Portland, Oregon.

Brown, G.W. 1969. Predicting temperatures of small streams. *Water Resour. Res.,* 5(1), 68-75.

Brown, G.W. 1970. Predicting the effect of clear cutting on stream temperature. *J. Soil Water Conserv,* 25, 11-13.

Brown, L.C. and T.O. Barnwell, Jr. 1987. The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS. *EPA/600/3-87/007,* Environ. Res. Lab. U.S. Environ. Prot. Agency, Athens, Georgia, 189 pp.

Burt, W.V. 1958. Heat budget terms for Middle Snake River Reservoir, in Water Temperature Studies on the Snake River, *Tech. Rep. 6*, U.S. Fish and Wildlife Serv., Washington, D.C.

Chapra, S.C. 1997. *Surface water-quality modeling.* McGraw-Hill Companies, Inc., New York, NY, 844 pp.

Cheng, R.T., V. Casulli, and S.N. Milford. 1984. Eulerian-Lagrangian solution of the convection-dispersion equation in natural coordinates. *Water Resour. Res.,* 20(7), 944-952.

Cole, T.M. and E.M. Buchak. 1995. A two-dimensional laterally averaged, hydrodynamic and water quality model. Version 2.0. US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Coutant, C.C. 1999. Perspectives on temperature in the Pacific Northwest's fresh waters. Oak Ridge National Laboratory, Environ. Sci. div. Pub. No. 4849 108 pp.

Dandy, G.C. and S.F. Moore, 1979. Water quality sampling programs in rivers. Journal of the Environmental Engineering Divsion, ASCE, 105: 695-712

Davidson, F.A. 1964. The temperature regime of the Columbia River from Priest Rapids, Washington to the Arrow Lakes in British Columbia. *Prepared for the* Public Utility

District No. 2 of Grant County, Ephrata, Washington. 31 pp. + tables and figures.

Delay, W.H., and J. Seaders. 1966. Predicting temperature in rivers and reservoirs. *J. Sanit. Eng. Div. Am. Soc. Civ. Eng.,* 92, 115-134.

Edinger, J.E., D.K. Brady, and J.C. Geyer. 1974. Heat exchange and transport in the environment. *Rep. 14*, 125 pp., Electr. Power Res. Inst., Palo Alto, Calif.

Foreman, M.G.G., C.B. James, M.C. Quick, P. Hollemans and E.Wiebe. 1997. Flow and temperature models for the Fraser and Thompson Rivers. *Atmosphere-Ocean*, 35(1), 109-134.

Gelb, A., J.F. Kasper, Jr., R.A. Nash, Jr., C.F. Price and A.A. Sutherland, Jr. 1974. *Applied Optimal Estimation*, 374 pp., MIT Press, Cambridge, Massachusetts

Hansen, A.J., Jr., J.J. Vaccaro, and H.H. Bauer. 1994. Ground-water flow simulation of the Columbia Plateau regional aquifer system, Washington, Oregon, and Idaho. U.S. Geological Survey Water-Resources Investigations Report 91-4187. Tacoma, Washington. 81 pp.

Hill, M.C. 1994. Five computer programs for testing weighted residuals and calculating linear confidence and prediction intervals on results from the ground-water parameter-estimation computer program MODFLOWP. U.S. Geological Survey, Open-File Report 93-481. Denver, Colorado. 81 pp.

Harrison, J., S. Wells, R. Myers and M. Kasch. 1999. 1999 Status report on Brownlee Reservoir water quality and model development – Draft Technical Report. Idaho Power Company, Boise, Idaho. 65 pp. + Appendices.

Independent Scientific Group. 1996. Return to the river: Restoration of salmonid fishes in the Columbia River ecosystem. Northwest Power Planning Council, Portland, Oregon. 584 pp.

Jaske, R.T. and M.O. Synoground. 1970. Effect of Hanford plant operations on the temperature of the Columbia River 1964 to present. *BNWL-1345.* Battelle Northwest, Richland, Washington.

Jobson, H.E. 1981. Temperature and solute-transport simulation in streamflow using a Lagrangian reference frame. *U.S. Geol. Surv. Water Res. Invest. Report No. 81-2,* 165 pp.

Kailath, T. 1968. An innovations approach to least squares estimation Part I: Linear filtering in additive white noise. *IEEE Trans. Auto. Contr., AC-13,* 646-655.

Karr, M.H., J.K. Fryer, and P.R. Mundy. 1998. Snake River water temperature control project-Phase II. Columbia River Inter-Tribal Fish Commission. Portland, Oregon. 209 pp.

Koivo, A.J. and G.R. Phillips. 1976. Optimal estimation of DO, BOD and stream parameters using a dynamic discrete time model. *Water Resour. Res*, 12: 705-711.

Lettenmaier, D.P. 1975. Design of monitoring systems for detecting trends in stream quality. Tech. Report No. 39, C.W. Harris Hydraulics Lab., University of Washington, Seattle, WA. 201 pp.

Lettenmaier, D.P. and S.J. Burges, 1976. Use of state estimation techniques in water resource systems modeling. Water Resources Bulletin, 12: 83-99.

Leopold, L.B. and T. Maddock. 1953. The hydraulic geometry of stream channels and some physiographic implications. *U.S. Geol. Surv. Prof. Pap., 252*.

Matalas, N.C. and T Maddock III. 1976. Hydrologic semantics. *Water Resour. Res.,* 12(1), 123-124.

McCullough, D.A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to chinook salmon. Prepare for U.S. EPA Region 10, Seattle, WA 279 pp.

McKenzie, S.W. and A. Laenen. 1998. Assembly and data-quality review of available continuous water temperatures for the main stems of the lower- and mid-Columbia and lower-Snake rivers and mouths of major contributing tributaries. NPPC Contract C98-002, Northwest Power Planning Council, Portland, Oregon.

Mehra, R.K. 1970. On the identification of variances and adaptive Kalman filtering. *IEEE Trans. Auto. Contr., AC-15*, 175-184.

Mehra, R.K. 1972. Approaches to adaptive filtering. *IEEE Trans. Auto. Contr., AC-17*, 693-698.

Mohseni, O, H.G. Stefan and T.R. Erickson. 1998. A nonlinear regression model for weekly stream temperatures. *Water Resour. Res.,* 34(10), 2685-2692.

Moore, A.M. 1969. Water temperatures in the Columbia River basin- Water Year 1968. Open-file report, U.S. Geological Survey, Portland, Oregon. 29 pp.

Moore, S.F. 1973. Estimation theory application to design of water quality monitoring systems. *J. of the Hydraul. Div. Am. Soc. Civ. Eng.*, 99(HY5), 157-181.

Moore, S.F., G.C. Dandy and R.J. deLucia, 1976. Describing variance with a simple water quality model and hypothetical sampling program. *Water Resour. Res.,* 12: 795-804.

Nelder, J.A. and R. Mead. 1965. A simplex method for function minimization. *Computing Jour.,* 7:308-313.

Normandeau Associates. 1999. Lower Snake River temperature and biological productivity modelling. R-16031.007 Preliminary Review Draft. *Prepared for the* Department of the Army, Corps of Engineers, Walla Walla, Washington. 119 pp. + Appendices.

O'Neill, K. 1981. Highly efficient, oscillation free solution of the transport equation over long times and large spaces. . *Water Resour. Res.,* 17(6), 1665-1675.

Oregon DEQ. 1998. Water quality limited streams 303(d) list. http://waterquality.deq.state.or.us/wq/303dlist/303dpage.htm.

Oreskes, N., K. Shrader-Frechette, K. Belitz. 1994. Verification, validation, and confirmation of numerical models in the earth sciences. *Science*, 263:641-646.

Press, W.H., B.P. Flannery, S.A. Teukolsky and W.T. Vetterling. 1986. *Numerical recipes: The art of scientific computing*. Cambridge University Press, New York, N.Y., 818 pp.

Rajaram, H. and K.P. Georgakakos. 1987. Recursive parameter estimation of conceptual watershed response models. IIHR Report No. 319. Iowa Institute of Hydraulic Research, Iowa City, Iowa. 169 pp.

Raphael, J.M. 1962. Prediction of temperature in rivers and reservoirs. *J. of the Power Div. Am. Soc. Civ. Eng.* , PO 2, pp. 157-181.

Rishel, G.B., J.A. Lynch, and E.S. Corbett. 1982. Seasonal stream temperatures changes following forest harvesting. *J. Environ. Qual.,* 11(1), 112-116.

Risley, J.C. 1997. Relations of Tualatin River water temperatures to natural and human-caused factors. *U.S. Geol. Surv. Water Res. Invest. Rept. 97-4071*, 143 pp.

Schweppe, F.C. 1973. *Uncertain Dynamic Systems.* Prentice-Hall, Inc. Englewood Cliffs, New Jersey, 563 pp.

Sinokrot, B.A. and H.G. Stefan. 1993. Stream temperature dynamics; Measurments and modeling, *Water Resour. Res.,* 29(7), 2299-2312.

Smith, D.J. 1978. Water quality for river-reservoir systems. U.S. Army Corps of Engineers, Water Res. Support Center, Davis, California.

Theurer, F.D., K.A. Voos, and W.J. Miller. 1984. Instream water temperature model. *FWS/OBS-84-15*, U.S. Fish and Wildlife Serv.

Thomann, R.V. 1982. Verification of water quality models. Journal of the Environmental Engineering Division, ASCE, 108: 923-940.

Valocchi, A.J. and M. Malmstead. 1992. Accuracy of operator splitting for advection-dispersion-reaction problems. . *Water Resour. Res.,* 28(5), 1471-1476.

Van Geer, F.C., C.B.M. Te stroet, Z. Yangxiao. 1991. Using Kalman Filtering to improve and quantify the uncertainty of numerical groundwater simulations I. The role of the system noise and its calibration. *Water Resour. Res.,* 27(8), 1987-1994.

USACE-HEC(U.S. Army Corps of Engineers). 1995. *HEC-RAS: River analysis system*. Hydrologic Engineering Center, Davis, California.

Washington DOE. 1998. Washington's final 1998 Section 303(d) list (impaired and threatened surface waters). http://www.wa.gov/ecology/wq/303d/

Water Resources Engineers. 1968. Prediction of thermal energy distribution in streams and reservoirs. *Prepared for The* Dept of Fish and Game State of California. Walnut Creek, California, 90 pp.

Wunderlich, W.O. and R. Gras. 1967. Heat and mass transfer between a water surface and the atmosphere. Tennessee Valley Authority, Div of Water Cont. Planning, Norris, Tennessee.

Yearsley, J.R. 1969. A mathematical model for predicting temperatures in rivers and river-run reservoirs. *Working Paper No. 65,* Federal Water Pollution Control Agency, Portland, Oregon.

Yeh, G.T. 1990. A Lagrangian-Eulerian method with zoomable hidden fine-mesh approach to solving advection-dispersion equations. . *Water Resour. Res.,* 26(6), 1133-1144.

Zhang, R., K. Huang, M.T. van Genuchten. 1993. An efficient Eulerian-Lagrangian method for solving solute transport problems in steady and transient flow fields. . *Water Resour. Res.,* 29(12), 4131-4138.